Power-to-X: The crucial business on the way to a carbon-free world

SIEMENS energy

siemens-energy.com/hydrogen

Dear readers,

We are happy to share some of our ideas and perspectives through this technical white paper.
Power-to-X is a key enabler for the energy transition. Why? Leveraging the potential from hydrogen in Power-to-X means, electricity is converted - preferably from renewable energy sources - to hydrogen or to hydrogen-based synthetic fuels and feedstock (like methane, methanol or ammonia). These can be stored, transported and used in all kinds of energy consuming sectors.
This is especially interesting for sectors where decarbonization via electrification is coming to its limits, for example where high energy densities and/ or high temperatures are required. This is the case in industry, mobility or heating sectors. So, sectors that formerly rather developed independently could be linked in the future via hydrogen. That's why we see hydrogen as a key enabler for sector coupling. Additionally, in the longer-term, hydrogen is a viable option to store excess electricity from wind or solar over longer periods and in huge amounts. Alternatively, it can be fed into (already existing) natural gas infrastructures.
Demand for hydrogen will potentially further increase. Sector coupling and further progress in fuel-cell technologies will foster the development of low-emission hydrogen technologies and allow to unlock economic and technologic value to the entire energy system.
I strongly believe that the next step of the global energy transition will be based on the hydrogen economy – taking "green electrons" and creating "green molecules". And by this sector coupling approach, we will decarbonize all applications where green electricity will come to its limits. I am really looking forward to shaping our green, sustainable future! Let's make it happen.

Prof. Dr. Armin Schnettler

EVP and CEO New Energy Business
Siemens Energy

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1. Why engage in Power-to-X

1.1 Fast decarbonization is a must

The climate crisis is palpable: According to the United Nations, storms, wildfires, droughts and other extreme weather phenomena fueled by climate change have hit 4.5 billion people in the past 20 years, and a study from the German insurance company Munich RE showed that the cost of these disasters in 2018 alone amounted to US$160 billion. The continued projections of damage caused by the emission of greenhouse gases are dire and incalculable: rising global temperatures, shrinking glaciers, warmer oceans, vanishing coastlines and increasing natural catastrophes.

Curbing the greenhouse effect has become one, if not the decisive factor for energy policies worldwide. In an effort to limit global warming to well below 2 °C above preindustrial levels, the Paris Agreement negotiated at the 2015 United Nations Climate Change Conference requires zero net emissions by 2045 to 2060. One hundred and seventy-four countries have signed the treaty, but political pressure in industrialized countries is mounting to increase the speed of transformation. In October 2018, the International Panel on Climate Change (ICPP) further reiterated the need for decarbonization and recommended an even more challenging target of limiting global warming to 1.5 °C by the end of the century, further increasing the pressure for transformation.

Enormous efforts and investments have been made to increase the share of electricity from renewables in the power sector up to 25 percent globally in 2017, but with little impact on global carbon emissions. As the power sector contributes to the global CO_2 emissions by only 40 percent, little progress in decarbonizing the remaining 60 percent from other sectors such as transportation, buildings, industry and others has been seen. In fact, greenhouse gas emissions have continued to peak year on year with a record increase of 1.7 percent in 2018.

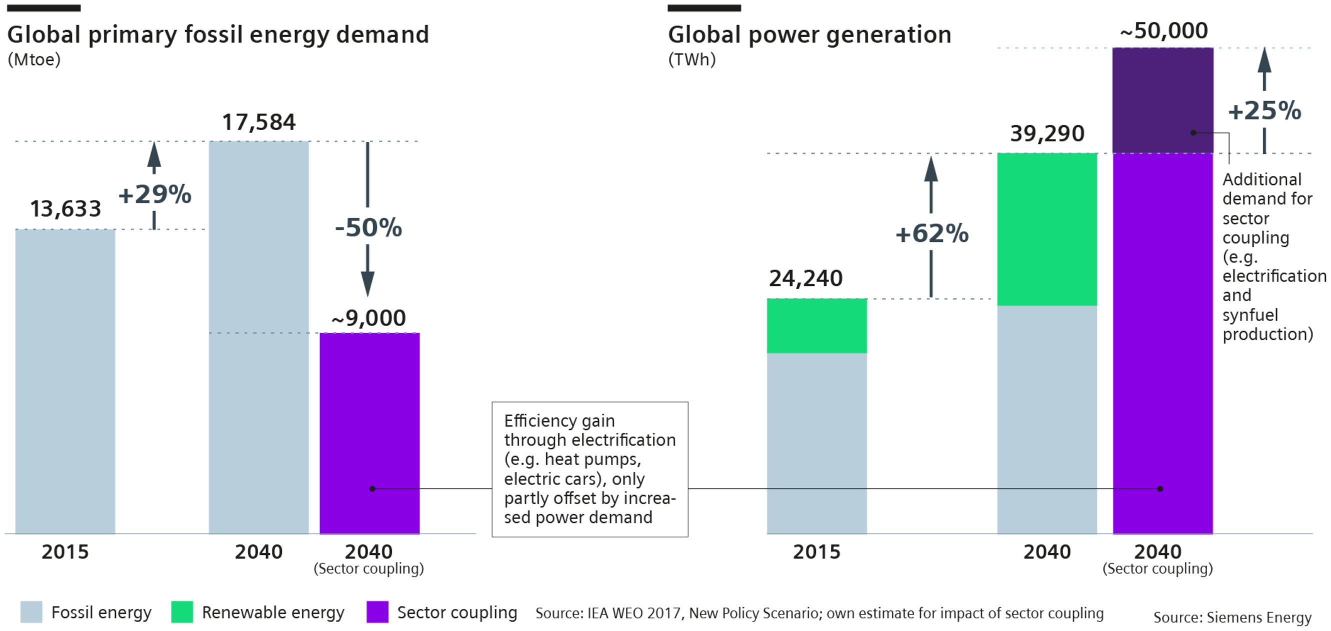
1.2 Sector coupling opens the whole energy landscape for renewable sources

In a fossil-dominated economy, decarbonization of sectors like industry, power, heating, gas or mobility was largely driven separately. To reach the target of net zero CO_2 emissions by mid-century, these separate sectors have to be integrated or coupled in order to provide renewable energy from the power sector to support their decarbonization. This sector coupling is a fundamental element of the energy transition. The blurring of industry boundaries becomes even more important as the installed capacity in renewable energy continues to rise. Already in some countries today, the power provided by wind and solar, by far the most important sources of renewable energy, supersedes the immediate consumption. As a result, many wind farms need to be curtailed when their power generation exceeds demand.

Using renewable electrical energy from the power sector to decarbonize energy across all sectors unlocks enormous environmental and business potential: Under certain conditions, we can demonstrate that sector coupling offers the potential to reduce primary fossil energy consumption by 50 percent. At the same time, power demand would need to increase by 25 percent, making the power sector the backbone of energy supply.

Power sector becomes the backbone of energy supply

With sector coupling, the increased electrification reduces primary fossil energy consumption significantly.



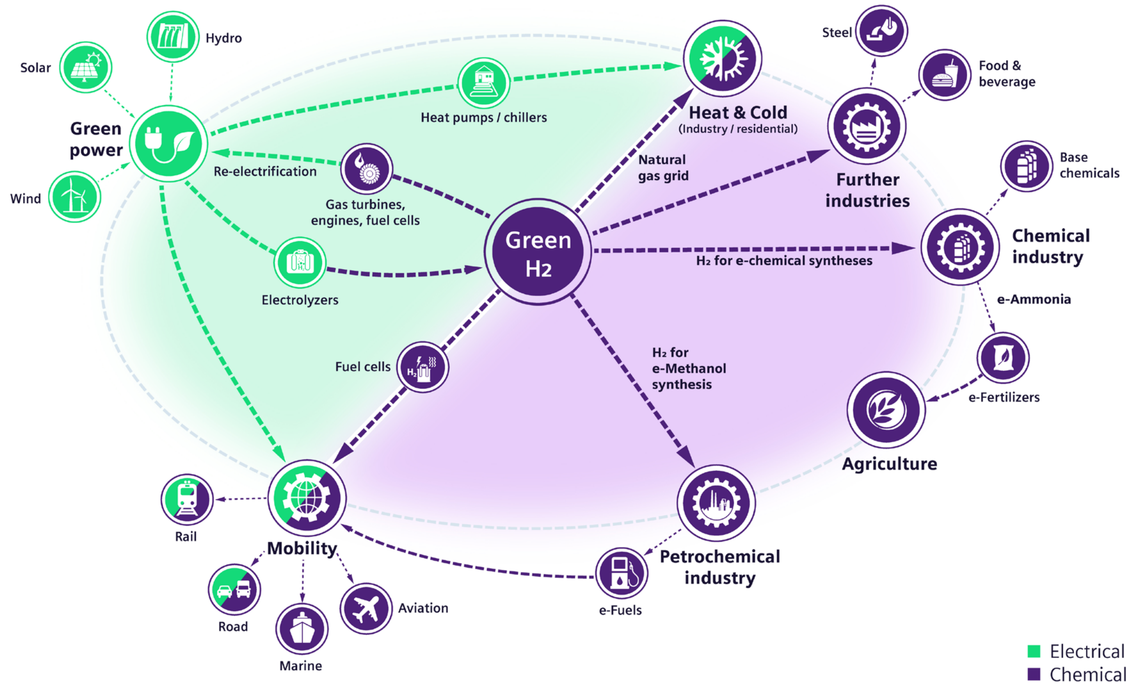
Source: IEA WEO 2017, New Policy Scenario; own estimate for impact of sector coupling

Source: Siemens Energy

However, coupling mostly volatile renewable energy resources with the different sectors leads to complex structures with the need for optimized operation and control modes. Digital solutions will play an important role in enabling such infrastructures.

1.3 Power-to-X is the important pathway

Power-to-X processes are the technological answer for sector coupling. For decades, combined heat and power generation (CHP) has been a success for maximizing the efficiency of fossil energy by using waste heat for the heating sector. Power-to-Heat via heat pumps or – simple, but less efficient – heating rods will now open a new green concept for heating buildings or even provide process heat for the industry. Electromobility, the direct use of electrical energy via batteries, is currently promoted in numerous countries, mainly for cars. No doubt – this is a major disruptive trend. However, electromobility is most likely not the answer for long-haul heavy transportation, marine and aviation. Here, energy-dense synthetic fuels generated from renewable electrical energy, called e-Fuels, should increasingly replace fossil fuels. These e-Fuels are similar to and can be mixed with conventional fuels in order to reduce the carbon content in the fuel mixture over time, without the need to change cars or the fuel logistics infrastructure. In this manner, the transition from a fossil world to a largely carbon-neutral environment can be done smoothly with immediate emission reductions on the way.



1.4 The core of Power-to-X is green hydrogen

Currently around 70-80 million tons of hydrogen are produced worldwide every year mostly from steam methane reforming or autothermal reforming. Fifty percent of this hydrogen is used for the synthesis of ammonia, which is the basis for ammonia phosphate or urea and other chemicals. Hydrogen is also used in refineries for hydrocarbon cracking and other processes. In the food industry, hydrogen is used for fat hardening.

The conventional method for producing hydrogen is the steam reforming process, in which steam reacts with natural gas to produce synthetic gas or syngas, a mixture of hydrogen and carbon monoxide. CO is shifted to CO_2, which is ultimately removed, but usually emitted to the atmosphere. If the CO_2 is sequestered, which is increasingly being considered by different companies, this fossil-based hydrogen can be produced without CO_2 emissions to a certain extent.

In comparison, the generation of green hydrogen via electrolysis of water with electrical energy from renewable sources is completely free of CO_2 emissions from the beginning. Hydrogen exclusively generated from electrical, renewable energy is also known as green hydrogen.

The discovery of electrolysis goes back to the year 1800, when the Italian physicist Alessandro Volta discovered that water molecules could be split into oxygen and hydrogen by means of an electric current. This discovery has become a key technology for the energy transition because the chemical bond energy in hydrogen can be extracted in many ways.

It can be easily stored and used either as a direct fuel for mobility or as a feedstock for various industries. Via synthesis with carbon dioxide (from unavoidable industrial emissions or from direct air capture) it can be converted into synthetic, sustainable e-Fuels such as e-Methanol, e-Methane, e-Diesel, e-Jet Fuel or other carbon-based chemicals. E-Ammonia from green hydrogen and nitrogen is another application.

In a vastly decarbonized world, green hydrogen will realize long-term, seasonal power-to-power storage on a large scale. Re-electrification will be realized in H_2-capable gas turbines, engines or fuel cells to provide security of electricity supply in periods of low renewable energy supply, e.g. lack of wind.

Power-to-X allows a smooth transition from the fossil world to a carbon-free one with increasing emission reductions on the way: E-Fuels can be mixed with fossil fuels to reduce the overall carbon footprint. A steady increase of sustainable content in the fuels allows for a gradual transition towards a full replacement of fossil fuels as a primary source of energy and raw materials in transportation, heating, industry and power generation.

1.5 Decarbonizing the world with Power-to-X could begin today

The transition to a carbon-free economy will need investments on a massive scale. Electric cars, for example, are only carbon neutral if the power fueling them comes from renewable sources. But the main impediment to changing the fleet today is the investment required to create a network of charging stations, and investors are hard to attract because the number of electric cars is still small. Moreover, long-distance modes of transportation, like heavy-load vehicles, prove more difficult to electrify without developing a trolley system or overhead lines, and ships or commercial aircraft cannot run on electricity alone. It's therefore unlikely that electromobility alone can achieve a significant reduction of greenhouse gas emissions in the coming years.

Power-to-X can produce fuels that have an immediate decreasing effect on greenhouse gas emissions: E-Methane, e-Methanol, e-Diesel, e-Gasoline or e-Jet Fuel can be used within existing fuel logistics infrastructures. While some synthetic fuels used today are produced from fossil sources, making them neither carbon-neutral nor carbon-free, synthetic e-Fuels from Power-to-X processes are different. These e-Fuels could also be produced with excess electricity from wind and solar farms, avoiding the current temporary reductions or shutdowns of these sources when they generate too much power for the grid.

The same holds true for the heating sector: Existing infrastructures such as gas pipelines, gas stations and storage facilities could be continuously used. And again, it holds true for power generation on a massive scale. Hydrogen is already suitable for re-electrification, since modern gas turbines can be operated with a hydrogen admixture in natural gas up to 100 percent. Hydrogen can therefore be stored in gas grids and re-electrified with gas turbines, using special burners to minimize NO_x emissions.

Sector coupling and Power-to-X is the way towards closed CO_2 cycles and CO_2 neutral infrastructures.

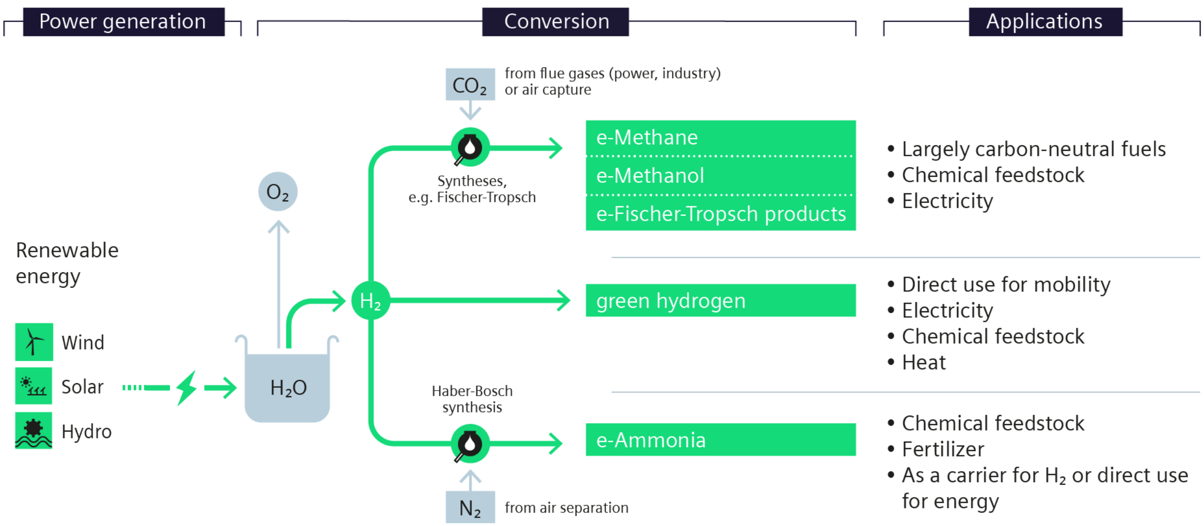
Renewable energies can be used to decarbonize many sectors of the economy. Together with energy-efficient technologies such as heat pumps, electromobility or combined heat and power plants, Power-to-X is critical to reducing CO_2 emissions. The synthesis of green hydrogen with CO_2 results in a largely closed CO_2 cycle: It is captured where the e-Fuels are produced and emitted where they are used, making these e-Fuels largely carbon-neutral.

Energy can be stored in huge quantities and for long periods of time within an already existing storage infrastructure, such as gas grids (hydrogen or e-Methane). Production peaks of volatile renewables can thus be stored for later use, increasing the security of supply. With Power-to-X solutions in large dimensions, renewable energies can also be used in far-off places where it's currently not viable because of nonexistent grids or a low requirement for electrical energy.

2. Technology: Power-to-X and use cases

Three pathways of Power-to-X

Electricity-based molecular hydrogen, methanol and hydrocarbons as well as ammonia.



Source: Siemens Energy

2.1 Power-to-Hydrogen

The Siemens Energy H_2 package comprises all systems to produce green hydrogen, including a PEM electrolyzer, compression and storage solutions.

An electrolyzer uses electricity to convert water into hydrogen. There are three types of electrolysis:

- solid oxide electrolysis, which is under development and currently introduced on small-scale,
- alkaline with high commercial maturity and operational experience, and
- proton exchange membrane (PEM) electrolysis.

With PEM technology, the electrolyzer can be switched on and off without preheating, leading to high flexibility and overall system efficiencies even at part loads. It is therefore perfectly suited for the load profiles of renewable power sources like wind and solar, which are volatile by nature.

Depending on the application, green hydrogen can then be purified and compressed to levels needed for direct use, storage or distribution.

As an energy carrier and base chemical, green hydrogen is used for different applications:

Electricity: through re-electrification: the high-capacity storage of electrical energy via green hydrogen and re-electrification in gas turbines (simple cycle and combined cycle), engines or fuel cells. This use is expected in the medium to long term.

Heat: the generation of especially high-temperature (process) heat by the combustion of green hydrogen or in a combined heat and power (CHP) process. Again, this use is expected in the medium to long term.

Mobility: By reducing the CO_2 intensity of conventional fuels and replacing fossil-fuel-based hydrogen in refining processes, the mobility sector can achieve around 10 percent decarbonization in the short term. In the long term, 100 percent decarbonization would be possible with additional new infrastructure, e.g. hydrogen stations and fuel cells.

2.2 Power-to-Methanol, Power-to-Hydrocarbons

Alternative pathways, especially essential for the decarbonization of the mobility sector, are e-Fuels synthesized from green hydrogen with CO_2, e-Methane (CH_4, via the Sabatier process), e-Methanol (CH3OH) or via the Fischer-Tropsch process electricity-based jet fuels, diesel or waxes (C_xH_y). These synthesis processes take place at elevated pressure levels (e.g. methanol synthesis at ~80 bar), are exothermal and catalytic. They are well established for syngas, a mixture of hydrogen and carbon monoxide, which is generated from fossil sources such as natural gas or coal. Applying carbon dioxide instead needs the conversion of CO_2 to CO in a separate process – the reverse water-gas shift. For e-Methanol different companies and institutes are developing commercially available processes for the direct conversion of hydrogen and CO_2. In contrast to conventional base-load operations of such processes in the chemical industry today, the production of e-Fuels needs to be viable for flexible load operation.

Together with biofuels, e-Fuels are highly relevant for reducing CO_2 emissions in the mobility sector: While still using the existing infrastructures (distribution, filling stations), about 50 percent of decarbonization is expected in the medium term with these largely carbon-neutral e-Fuels. Carbon will be used as a carrier to bring renewable energy as e-Fuels into today's infrastructure (state-of-the-art fuel station systems, ships, aviation), bridging new and existing technology.

In that context e-Methanol is of special importance for the mobility sector: For example, China today uses about a third of its still fossil-fuel-based methanol production for transportation (in different qualities, M15 to M100). In Europe, already today about 3 percent of methanol could be admixed to fossil gasoline. Producing it from renewable energy sources would directly avoid the net CO_2 emissions stemming from the conventional supply chain. Via the Methanol-to-Gasoline (MtG) process, fully sustainable e-Gasoline could be produced. Other subsequent products are fuel additives (MTBE), formaldehyde, formic acid or olefins (MTO).

Power-to-Carbon-based e-Fuels open a way for decarbonizing the transportation sector beyond the gains reached through electromobility. Main applications are seen for trucks, ships and in aviation.

2.3 Power-to-Ammonia

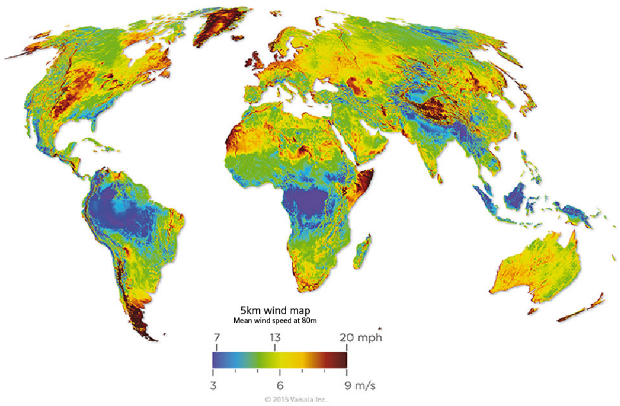
E-Ammonia (NH_3) is synthesized from green hydrogen and nitrogen derived from an air separation unit. The underlying Haber-Bosch process is well established. E-Ammonia can be used as feedstock for fertilizers (urea, ammonia phosphates), other chemicals and potentially synthetic e-Fuels (e.g. for shipping industry). With about 175 kilograms of hydrogen per ton of ammonia, it is an excellent carrier of hydrogen to transport it over far distances using the existing infrastructure. For regaining, the hydrogen ammonia cracking processes are under development.

3. Down to business: economic feasibility and drivers

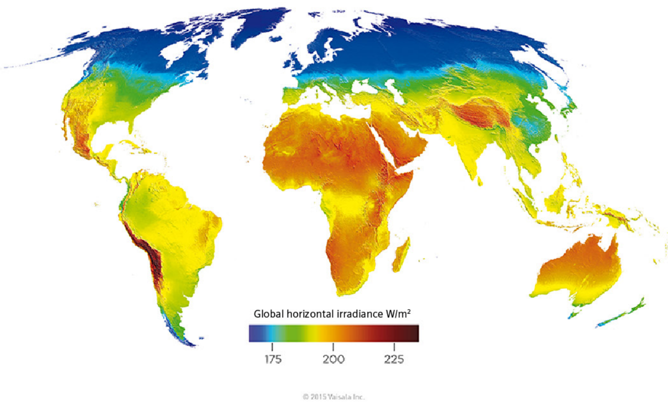
3.1 Production of e-Fuels under best local conditions

With green hydrogen positioned to become an important component of a decarbonized world, the demand for hydrogen is already rising and set to rise even more in the future. Production costs for renewable energy have dramatically decreased over the last decade. Levelized cost of electricity (LCoE) for onshore wind power has been shown to fall below US$20/MWh in the USA and Mexico. The same applies to solar power in different regions.

There are many regions worldwide benefiting from the generation of power from renewable sources



Global wind map



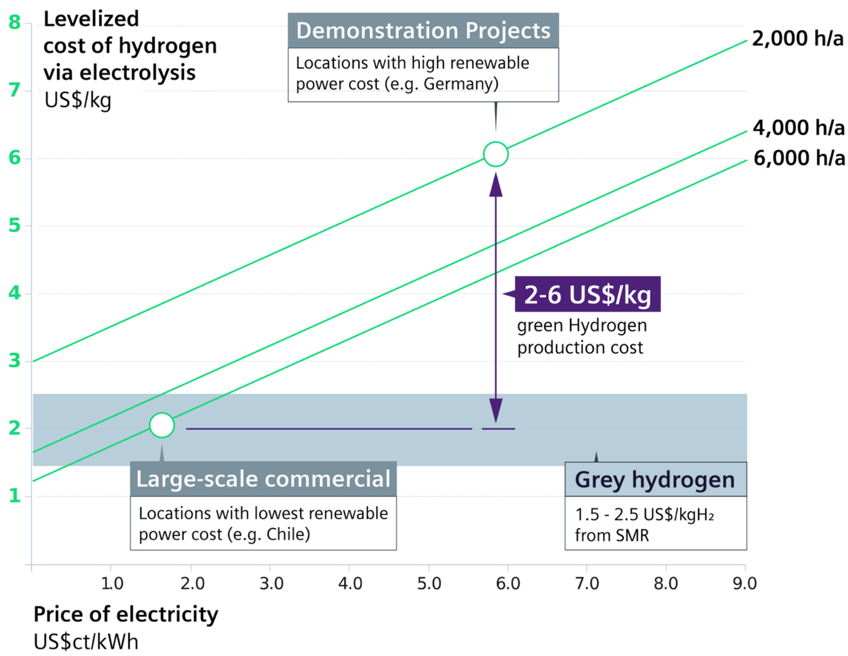
Global solar map

Graphics from Tanja Siegel – independent-medien-design.de

In addition to the electricity generation cost, the capacity factor (full-load hours) of the electrolysis is the dominant aspect for the cost of green hydrogen, defining the capital efficiency of the electrolyzer and synthesis plant. With favorably LCoE of US$20/MWh and 6,000 full-load hours availability for some locations, green hydrogen generated from electrolysis can already compete with hydrogen from steam-methane reforming or autothermal reforming of natural gas.

Hydrogen from electrolysis becomes competitive

Highly available, low-cost renewable power already generates green Hydrogen at costs of conventional hydrogen from steam methane reforming (SMR).



Source: Siemens Energy

Main impact by WACC; electrolyzer_CAPEX, OPEX, electrolyzer efficiency, lifetime

The capacity factor of electrolysis is as important as the levelized cost of electricity because it defines the capital efficiency of the electrolysis plant. Considering today's prices for hydrogen at fueling stations, even in some European countries, e.g. in Switzerland, green hydrogen would make a positive business case.

The specific investment cost of electrolysis will be reduced by upscaling, improving the manufacturing process (automation) or substituting high-cost materials and using different technologies.

Already today, e-Fuels are competitive for regions with the best conditions for renewable energy sources. Since the costs for green hydrogen also affect the production costs for e-Fuels, it's not surprising that in those regions prices for e-Fuels, first of all e-Methanol, are below the levels that can be achieved for other sustainable green fuels in the transportation sector today. Bioethanol is the benchmark.

Another factor affecting the production of carbon-based e-Fuels is the cost for CO_2 supplies. CO_2 can be captured from existing, unavoidable point sources, e.g. from cement production, biomass power plants or (future) system-relevant, natural-gas-fired power plants. Using direct air capture (DAC) to recover CO_2 from the atmosphere might also be an option in the future, especially for regions rich in renewable energy, but far away from industrial sites.

3.2 Power-to-X can contribute to grid balancing

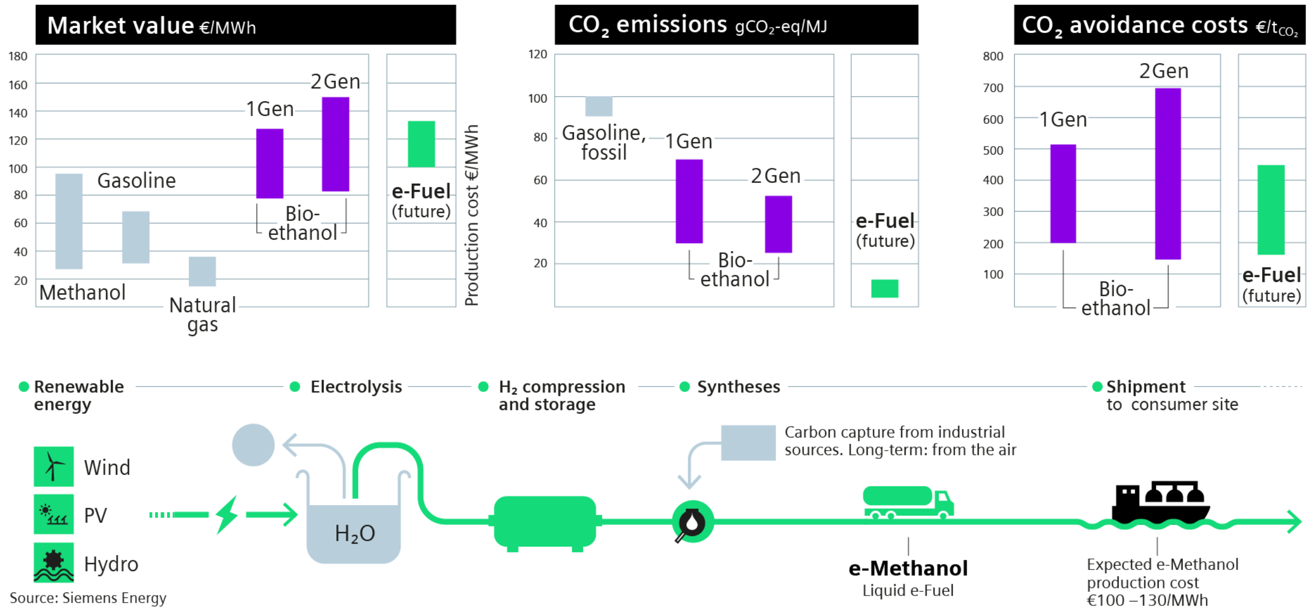
Electrolysis could act as a fast-negative energy balancing unit in the event the grid is overloaded from renewable energy sources (RES). Large overcapacities of RES already exist today. Storing the surplus electrical energy of those sources in chemical form may become more lucrative than curtailing the capacity of renewables in peak production times. Green hydrogen and its subsequent fuels derived from RES are expected to become the backbone of future, largely decarbonized power generation, because chemically stored electrical energy is the only way to overcome lacking renewable sources or times where there is little or no wind or sun.

3.3 E-Fuels outperform biomass-based fuels

E-Fuels have a carbon footprint that is about 90 percent lower than that of fossil fuels. Against this background, e-Fuels like e-Methanol have the potential to outperform biofuels in terms of production costs and CO_2 avoidance costs. Their overall benefits in comparison to biomass-based fuels and chemicals are numerous: Overall greenhouse gas emissions of e-Fuels are equal to or lower than those of biomass-based fuels, and the same applies for land use and needs for water. The conflict between food and fuel is nonexistent in e-Fuels, and their global availability is potentially high in many regions worldwide.

Economic viability

Electricity-based fuels might be cost-competitive to biofuels and could result in lower CO_2 mitigation costs.



Source: Siemens Energy

3.4 Regulatory inducements are still needed

Although investment costs for Power-to-X will decrease during the next years according to technology development, regulation and political support are needed to push the introduction of e-Fuels.

According to the most recent regulatory framework, the second European Renewable Energy Directive (RED II), which has to be converted into national laws by June 2021, the minimal share of renewable energy sources in fuels has to grow from 5 percent today to 14 percent in 2030. About a quarter is expected to come from direct electrification (electromobility). Additional biomass-based fuels will only be allowed from nonfood relevant sources (2nd generation) and must contribute a minimum 3.5 percent. To reach the European targets additional advanced fuels based on renewable electrical energy have to be increasingly applied up to three-digit petajoule levels. To achieve this, e-Fuels will also have to be imported from outside Europe, which has to be considered by the regulatory bodies. The German BImSchV38 decree already implemented advanced fuels which are defined as fuels produced from captured CO_2 with the condition to use renewable energy for their production. Aside from taking CO_2 from the air or biomass conversion, CO_2 can also be sourced from unavoidable emissions from industries and power plants.

From the different use cases, such as direct use of green hydrogen for trucks or as substitute for natural gas or e-Fuels for aviation, Siemens Energy is expecting a market potential in the range of some billion euros per year.

4. Hand in hand: solutions provided by Siemens Energy

Siemens Energy is one of the world's leading technology companies and one-stop solution providers. Working hand in hand with its clients to develop and provide technologically mature solutions that present a business case, Siemens Energy can look back on a long and successful experience in plant construction as well as in development, production, operation and service of diverse products of power generation; the same goes for energy transmission, electrical engineering, automation technology, communication and automotive technology – based on its competence and experience.

Siemens Energy can offer several Power-to-X plant modules and overall solutions for different use cases. To cater to each customer according to need, Siemens Energy is following a modular structured approach: modules and packages for Power-to-X applications as well as the Engineering, Procurement and Construction (EPC) of an overall Power-to-X plant as a turnkey package.

Models and packages offered by Siemens Energy follow the process steps:

Power-to-X system design package: this offering helps customers to gain transparency on options and opportunities related to their Power-to-X solution at an early decision stage.

Renewable power package: offers a renewable energy supply, including grid connection or as a captive power supply for the Power-to-X plant. Wind turbines onshore and offshore as well as complete wind parks and renewable energy solutions.

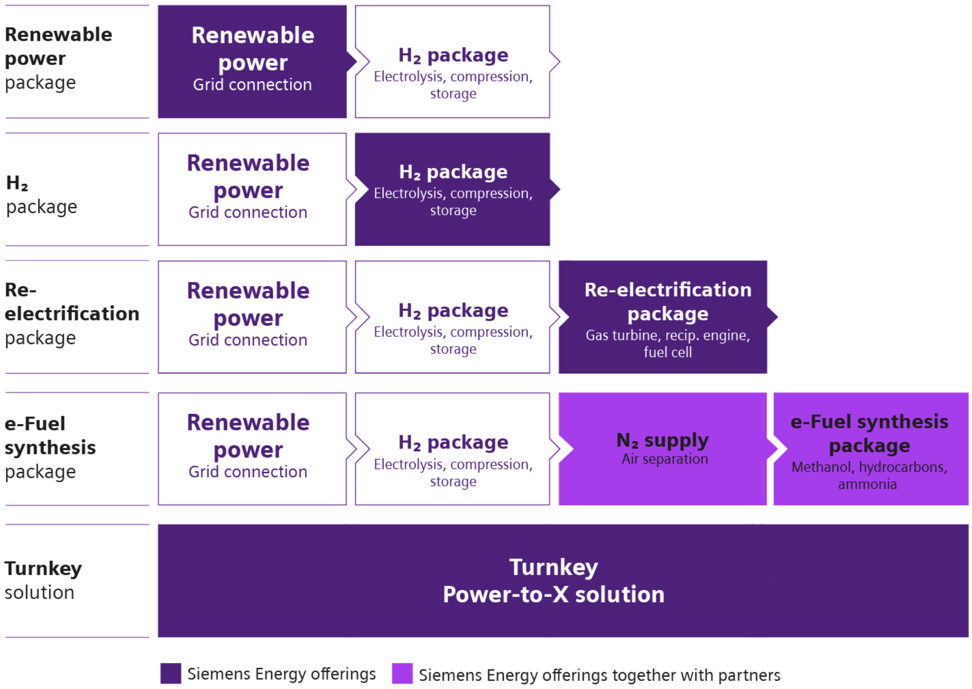
H_2 package: offers electrolyzer, hydrogen compression and intermediate storage.

Re-electrification package: Designed to the needs of the client, this package offers long-term hydrogen storage, a hydrogen gas turbine/combined cycle power plant, reciprocating engine, fuel cell or battery energy storage system.

E-Fuel synthesis package: Developed and/or supplied together with partners, this package includes compression and synthesis.

Power-to-X turnkey package: the full turnkey solution for any of the packages or applications as shown below. 100% hydrogen compatible well before 2030, and therefore, e-Ammonia may also be a useful hydrogen carrier for heating, industrial use, and combustion power systems.

Siemens Energy offers a modular approach for Power-to-X plants



Source: Siemens Energy

4.1 Siemens Energy H_2 package

The Siemens Energy hydrogen generation plant is a facility that integrates key technologies to produce green hydrogen. This innovative solution will serve, connect, transform and reduce carbon emissions in multiple industries. It is the basic module of the Siemens Energy Power-to-X plant solutions.

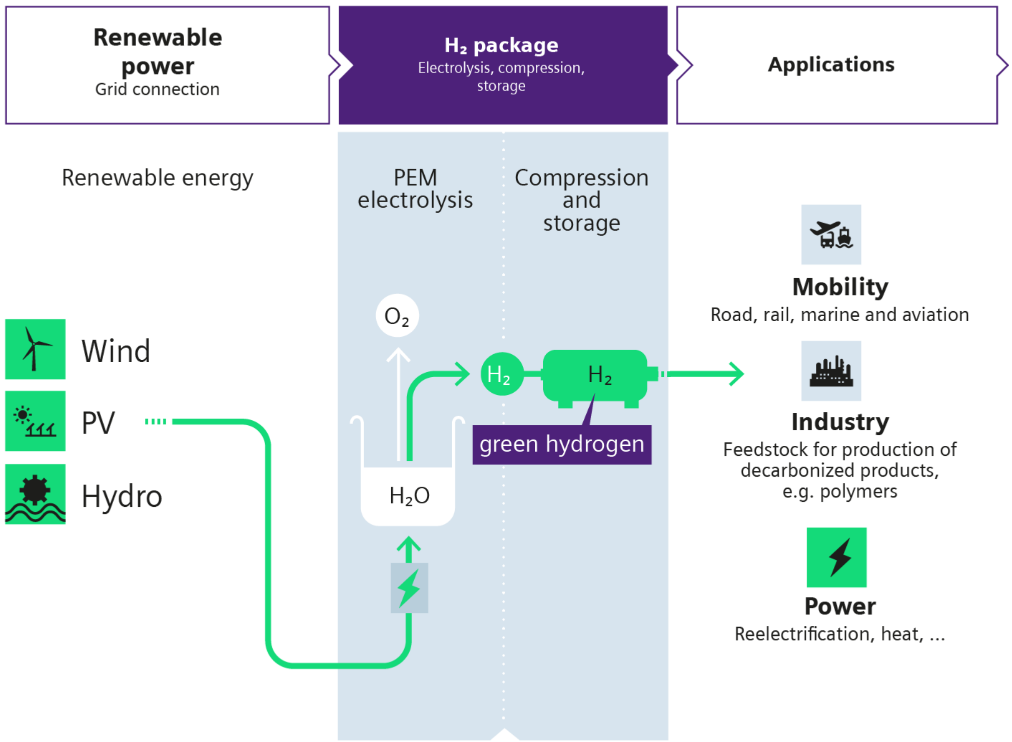
Siemens Energy is providing the full EPC for this package, comprising of:

- electrical equipment (transformer, switchgear, rectifier, etc.),
- treatment and deionization of water as needed,
- PEM electrolyzer and its connection to the power source (see following section),
- cleaning of green hydrogen, e.g. gas conditioning according to the needs of the downstream application,
- gas storage, and
- compression of green hydrogen with reciprocating or turbocompressors, depending on final pressure level and mass flow.

Due to its low molecular weight and its chemical characteristics, the effective and safe handling of hydrogen needs specific solutions, products and know-how. Gases containing hydrogen require a limitation of yield strength and hardness according to API 617. Of course, this is part of the Siemens Energy designs.

The Siemens Energy H2 package

Pressurized and purified hydrogen from renewable energy sources



Source: Siemens Energy

Electrolysis

In order to produce green hydrogen, Siemens Energy has developed the Silyzer portfolio family: an innovative electrolysis system based on PEM technology. PEM takes its name from the proton exchange membrane, which is permeable to protons (H+) but tight for gases and electrons. In other words, this kind of membrane acts as electrical isolator between anode and cathode side as well as physical separator, preventing hydrogen and oxygen from remixing. Compared to alkaline electrolysis, PEM technology is ideal for working with fluctuating wind and solar power sources, as it allows a highly dynamic mode of operation and can be rapidly turned on and off without preheating. This method allows optimum efficiency at high power densities and good product gas quality even at partial loads. The operation is low-maintenance and reliable without the use of chemicals or foreign substances.

Advantages of industry-grade PEM technology in brief:

- delivers pure hydrogen and oxygen of the highest quality, free of hazardous substances,
- provides flexibility with a very fast start-up time and allowing rapid load changes
- reliable operation with low maintenance requirements
- compact design comes along with low space requirements.

All safety aspects in the production and handling of hydrogen are implemented through permanent detection systems and hoods.

Service packages are offered according to the individual customer’s requirements:

- basic: support and troubleshooting on demand,'
- advanced: preventive maintenance, remote service, condition monitoring, 24/7 hotline and more,
- pro: performance-based maintenance contracting.

Since PEM electrolysis technology and its most prominent representative, the Silyzer, is a relatively young technology, additional improvements to efficiency and investment cost reductions are expected. A strong increase in production capacities over the next decade will also see further advancements and savings. After the successful introduction of the Silyzer 300, the next step will be a PEM model in the range above 100 megawatts. In parallel the next generation of more economic cells are under development.

Silyzer 300

This latest, most powerful product line in the double-digit megawatt range allows for the best scaling to minimize overall investment costs in large-scale industrial electrolysis plants. Thanks to high plant efficiency and availability, the optimized solution results match very low hydrogen production costs. Further indicators: 17.5 MWel /335 kg/hour per full module array (24 modules), 75 percent system efficiency (HHV).

Compression and storage

Compressors are a vital component of most of the Power-to-X plants:

- Power-to-Hydrogen: Compressors compress hydrogen for storage or refueling to pressures as high as 700 bara.
- Power-to-Fuels: Compressors compress hydrogen or the mixture of hydrogen and CO_2 to approximately 70 bara for subsequent synthesis of methanol.
- Power-to-Ammonia: Compressors compress hydrogen or the mixture of hydrogen and nitrogen to approximately 300 bara for subsequent synthesis of ammonia.

For all these cases, Siemens Energy offers a broad spectrum of compressors designed to fit customer specifications. Compression solutions can be supplied in a variety of configurations from single-shaft barrel to reciprocating compressors. Siemens Energy has a long experience with compressors for gases containing hydrogen, such as synthesis gases to produce ammonia, hydrocarbons and methanol as well as hydrogen-rich gases. Steam turbines, engines or electrical motors are used as drives.

References in the field of sustainable hydrogen production

With three Silyzer 200 systems, the Energiepark Mainz was the world’s largest PEM electrolysis plant in 2015. It uses excess energy from renewable sources (wind) to split water into oxygen and hydrogen. The regeneratively produced hydrogen is fed into the gas network on site or delivered to the surrounding industry and hydrogen filling stations via tankers. The entire electrolysis plant, including the grid connection and control system, was supplied by Siemens Energy.

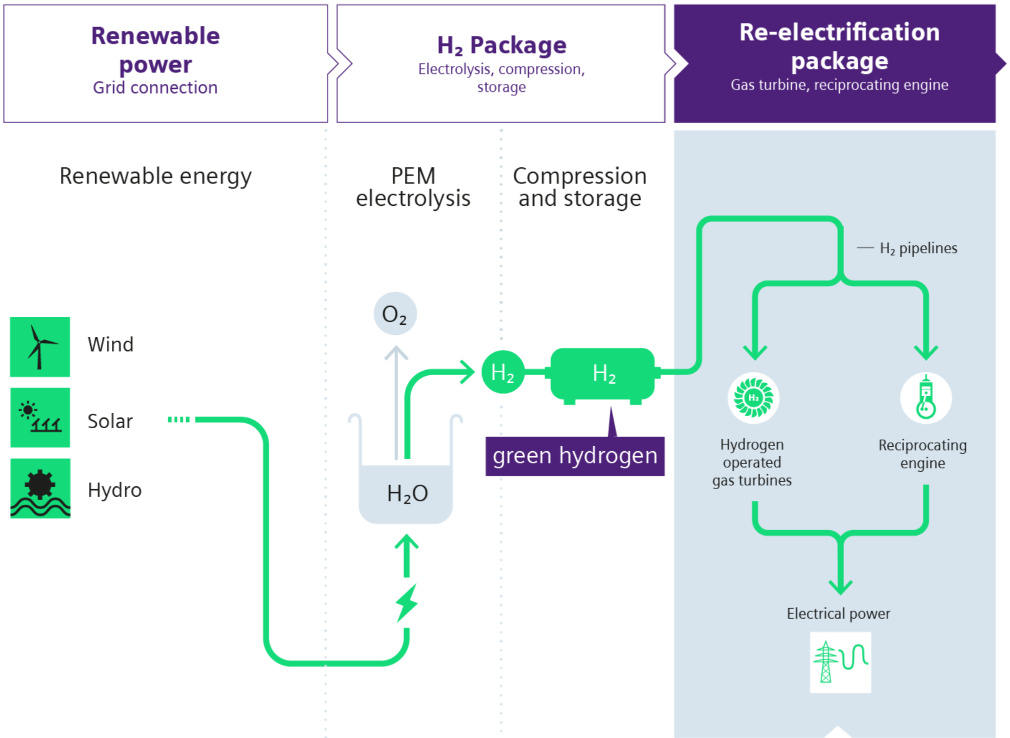
The EU-funded lighthouse project “H2FUTURE - hydrogen meeting future needs of low carbon manufacturing value chains” brings together energy suppliers (Verbund, APG), the steel industry (Voestalpine), technology providers (Siemens Energy) and research partners (K1-MET; TNO) to jointly develop solutions for the energy future. With an output of 6 megawatts and a production capacity of 1,200 cubic meters of hydrogen per hour, H2FUTURE was the world’s largest hydrogen pilot plant in 2019 in which green hydrogen is produced from renewable sources using PEM electrolysis technology with the Silyzer 300. The PEM electrolysis plant started operation in November 2019 at the largest steel production site of the Voestalpine Group in Linz, Austria. The project aims to demonstrate that an industrially integrated PEM electrolysis plant is capable of producing green hydrogen and providing grid services at the same time.

4.2 Siemens Energy re-electrification package

Even though hydrogen is considered one of the most promising technologies in the large-scale integration of renewable energy, only a small percentage of hydrogen is currently being used in the energy sector. Yet the more electricity is generated from fluctuating renewable sources such as sun and wind, and the less reliance there is on conventional power utilities, the more urgent becomes the need to change energy systems. After all, power must also be available when sun and wind are scarce. This requires storing energy, including over extended periods of time. Green hydrogen plays a key role in this regard, as an energy source as well as a storage medium. Infrastructure suitable for large-scale storage includes gas grids, which have tremendous storage potential. The re-electrification of stored green hydrogen offers the advantage of using decarbonized renewable electrical energy whenever required.

The Siemens Energy re-electrification package

Long experience with hydrogen in gas turbine fuels



Source: Siemens Energy

The primary source is green hydrogen generated in the H_2 package from Siemens Energy, including storage. Re-electrification of the green hydrogen is done either by combustion, preferably in an adapted gas turbine in combined cycle mode, in a reciprocating engine or in fuel cells to generate electrical energy. This arrangement can also be combined and/or extended with battery energy storage (BES) in a hybrid generation unit to further increase flexibility.

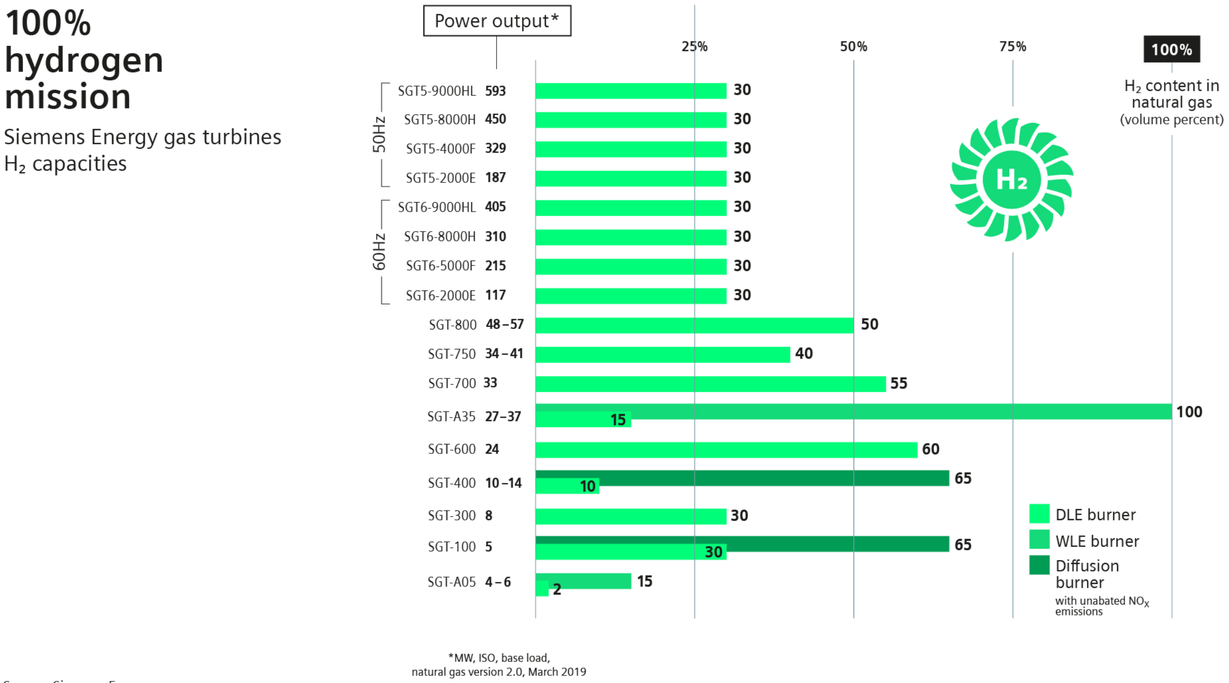
Siemens Energy is providing the full EPC for this re-electrification package, comprising:

- fuel system (incl. admixing other fossil fuels or steam, where needed),
- combined heat and power (CHP) plant for power and district/process heat production
- reciprocating engine,
- fuel cell (supplied by partner),
- BES in case of a hybrid system, and
- grid connection.

4.2.1 Gas turbines

Gas turbines make up a core component of Siemens' history. In 1949, Siemens started its first engine, the VM1. Based on these 70 years of experience in designing and manufacturing gas turbines, Siemens Energy today provides a wide portfolio of products that can be operated with a mix of hydrogen and natural gas or with pure hydrogen.

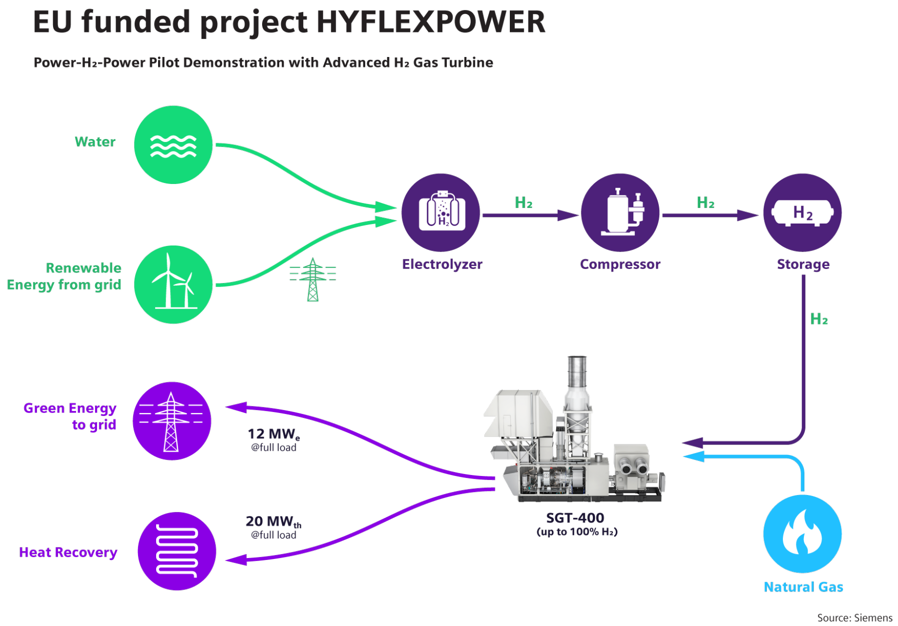
Already natural-gas-fired gas turbine power generation units boast a much higher efficiency level and lower CO_2 emissions than coal-fired plants. By mixing green hydrogen together with natural gas or even substituting natural gas altogether, these CO_2 emissions can be further reduced until, ultimately, they reach zero. Most Siemens gas turbines are already capable to burn between 30 and 100% of H_2, depending on the frame type. Continuous development and options for upgrades will make them ready for 100% H2 before 2030, according to its availability in a sustainable form.



Source: Siemens Energy

References for re-electrification packages

In May 2020, with the HYFLEXPOWER project, a consortium made up of Siemens Energy, Engie Solutions, Centrax, Arttic, German Aerospace Center (DLR) and the University College London, University of Duisburg-Essen, Lund University and National Technical University of Athens are implementing a project funded by the European Commission under the Horizon 2020 Framework Program for Research and Innovation (Grant Agreement 884229). The implementation of this project, the world's very first industrial-scale Power-to-hydrogen-to-power demonstrator with an advanced hydrogen turbine, will be launched at Smurfit Kappa PRF's site - a company specialized in manufacturing recycled paper - in Saillat-sur-Vienne, France. The purpose of this project is to prove that hydrogen can be produced and stored from renewable electricity and then mixed with the natural gas currently used with combined heat and power plants. For this an existing Siemens SGT-400 industrial gas turbine will be upgraded to convert stored hydrogen into electricity and thermal energy, with the aim of achieving 100% hydrogen combustion by 2023.



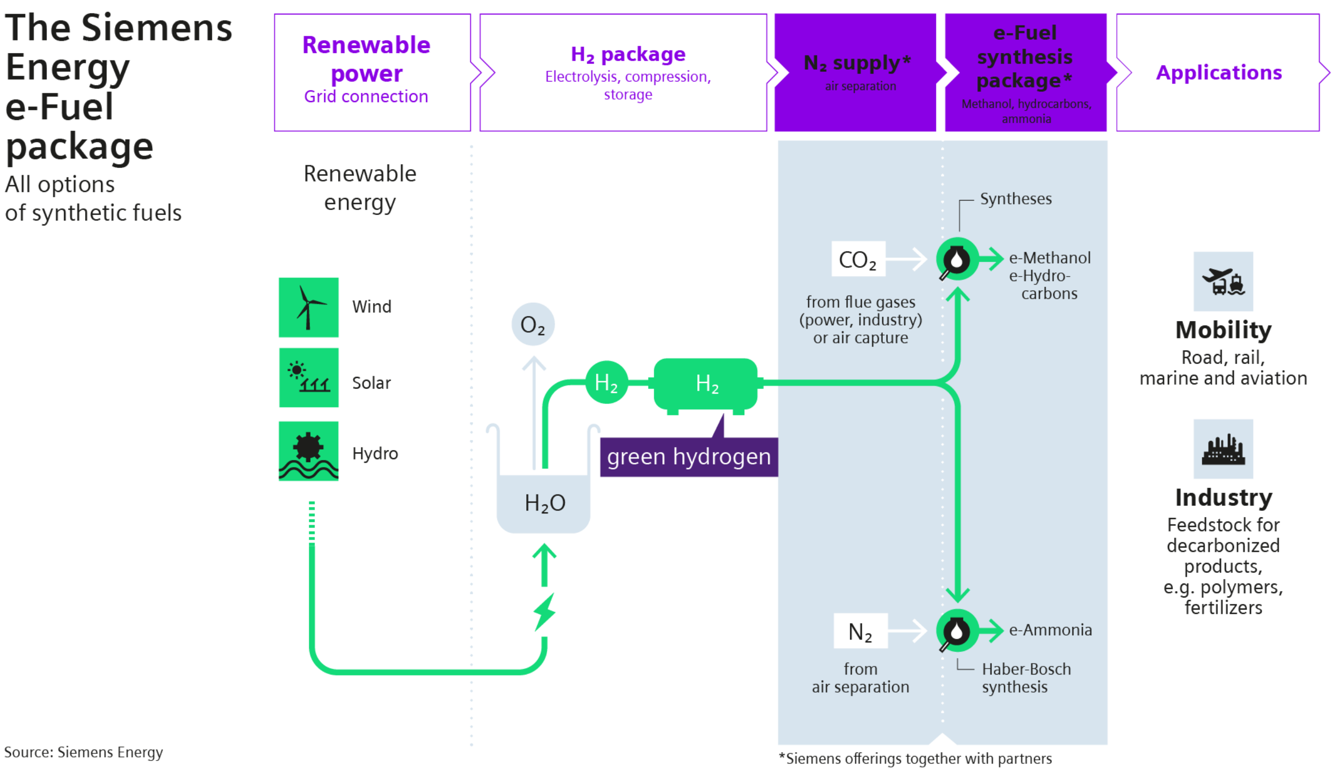
4.2.2 Reciprocating engines/fuel cells

Besides the installation of a gas turbine for large-scale re-electrification, green hydrogen can also be used for gas engines (on the thermal side) or fuel cells (on the chemical side). The products available are either from Siemens Energy branches or supplied by our solution partners. Siemens Energy offers these products fully engineered and optimized for the specific use case.

4.3 Siemens Energy e-Fuel package

Another way green hydrogen can contribute to decarbonization is through the synthesis of carbon-based e-Fuels from green hydrogen. In this way, even sectors with high fuel requirements, such as the aviation and shipping industries, could be decarbonized to a large extent. A prominent use case is e-Methanol for transportation. Other applications include e-Methane or e-Ammonia.

The primary source is green hydrogen generated in the H_2 package from Siemens Energy. Hydrogen is then further processed through, for instance, methanol synthesis or the Fischer-Tropsch process. The CO_2 can be gained from inevitable emissions, for instance from cement production, glass or steel. Alternatively, CO_2 could also prospectively be extracted from the atmosphere (direct air capture – DAC).



Source: Siemens Energy

For e-Ammonia the system includes the nitrogen supply, for instance by a cryogenic air separation unit.

Siemens Energy together with partners is providing the full EPC for this package, comprising:

Compression and pumping of involved media

Carbon capture, oxyfuel and direct air capture with partners;

Synthesis processes with partners – direct from CO_2 and H_2 without the need for reverse water-gas shift.

4.3.1 CO_2 capture

Carbon capture is expected to play a vital role in Power-to-X to produce green fuels from electrolysis. To reduce the footprint of e-Fuels compared to fossil fuels, the origin of the CO_2 plays a decisive role. In general, three categories of origins contribute to a reduced carbon footprint of the fuel:

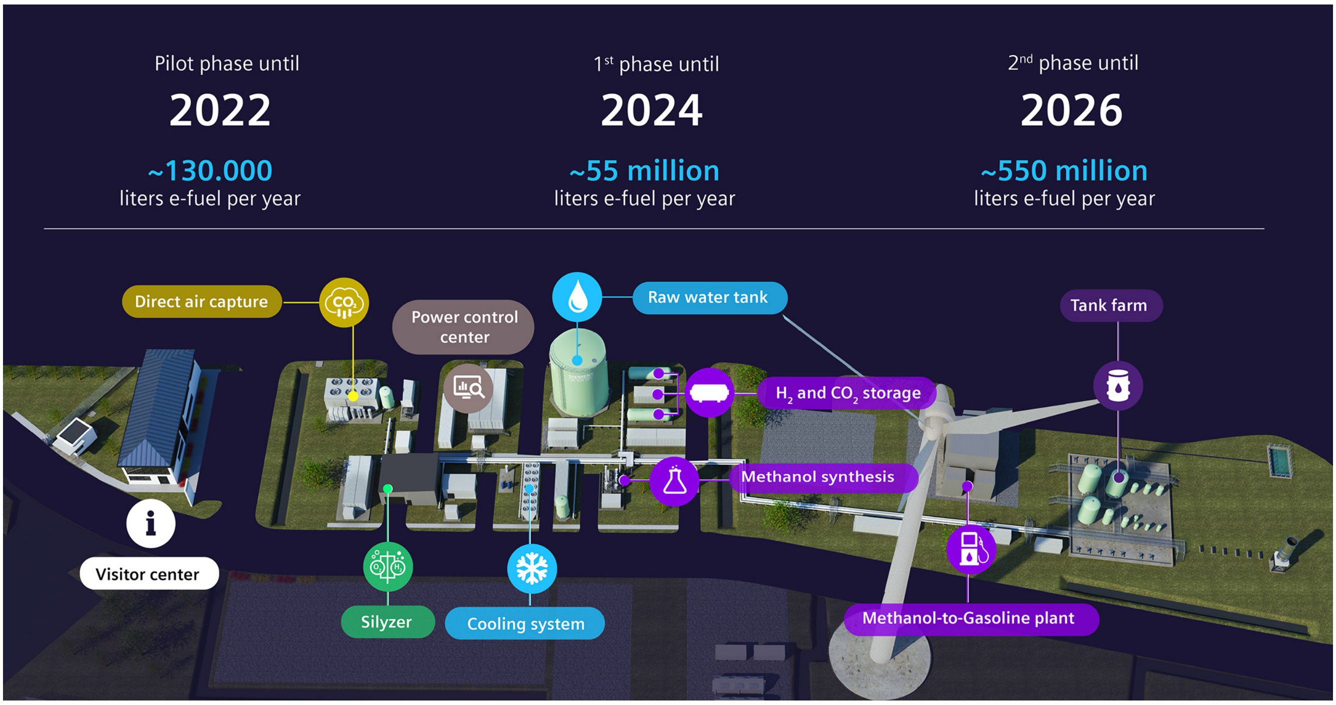
- CO_2 from biogenic sources, such as biomass,
- CO_2 from unavoidable emissions, mainly industrial emissions such as from cement plants,
- CO_2 from the atmosphere through direct air capture (see below).

Alternatively, carbon dioxide can be produced through combustion in oxyfuel boilers with hydrocarbons from various sources.

Direct air capture (DAC): The atmosphere contains only a very low concentration of around 400 ppm CO_2, but the increase of this concentration is considered to be the trigger for global warming. There are currently a few technological developments being piloted to extract CO_2 from the atmosphere through adsorption, though costs are still significantly higher than with alternatives from other sources.

References for Methanol synthesis

For commercial plants Siemens Energy is collaborating with companies well experienced in CO_2/H_2-based methanol synthesis using established reactor concepts. In November 2020, Siemens Energy, alongside several international companies, announced it is developing and implementing Haru Oni, the world's first integrated and commercial large-scale plant for the production of climate neutral e-Fuel in Chile. In the pilot phase, e-Methanol production will initially reach around 750.000 liters per year by 2022. Part of the e-Methanol will be converted to e-Gasoline (130.000 liters per year). In two steps, capacity is planned to be increased to 55 million liters e-Gasoline per year by 2024 and to over 550 million liters per year by 2026.



References for Ammonia synthesis

Ammonia synthesis from hydrogen and nitrogen applying the Haber-Bosch process has been well established for decades. Here, Siemens Energy would partner with an experienced supplier in the frame of EPC delivery. This also includes the nitrogen supply.

In the context of an R&D project with British academia, Siemens Energy gained experience in research, setting up and operating a small, but fully complete Power-to-Ammonia plant working in dynamic mode. This includes re-electrification in a reciprocating spark-ignition engine.

4.4 Digital solutions and Power-to-X system design package

Digitalization, currently one of the most important topics in the energy industry in general, is an important component for the realization of Power-to-X along the whole value chain. On the one hand, digital investments are triggered by market requirements, such as growing shares of renewables in the electricity grid which need to be integrated in the current energy mix and in the same time the grid stability must be given.

On the other hand, new technical solutions for power plant equipment also drive digitalization. Here can it be helpful to use Energy System Design. It is an integration method that connects all processes and products to complete the end-to-end value chain for the customer.

Energy system design and solutions are a core element of digital services that help customers to gain transparency on options and opportunities at an early decision stage. With our Power-to-X system design package Siemens Energy provides deep know-how and consulting service based on for energy system design in development of decarbonization roadmaps & solutions for customers across wide range of industries, mobility and energy production.

Siemens Energy engineering competences & dedicated tools for energy system design, optimization and simulations will be leveraged to identify optimal techno-economic recommendations for solutions.

Having our customers' specific needs at the core from the earliest project stage, is essentially. Therefore also the services are continuously developed over the project life span to enhance availability, operations, maintenance cycles, performance and commercial viability of the most different use cases.

Siemens Energy is a world market leader for power plant automation as well as for factory and industrial automation. Several systems are available to control processes in the optimum way, amongst them the SIMATIC product portfolio, SPPA products or SICAM. Since electrolysis and, more generally, Power-to-Gas and Power-to-Liquids are related to chemical processes, Siemens Energy has already implemented a proven process control system. Experiences gained from pilot and demonstration plants can be optimally translated to upscaled commercial plants. This has already been done for the Silyzer products and the 6-megawatt Power-to-Methane plant in Werlte, Germany, which produces e-Methane for gas-fueled cars. In addition to diagnostics, the remote access automation system is used to optimize the overall concept. Future approaches to digitalization will support this in the context of available renewable energy sources and different products.

Siemens Energy has already implemented predictive controls in comparable applications. By combining weather forecast information with optical information of upcoming cloud coverage, detailed forecast for PV power generation has been made possible. This combination of information is key to optimize performance of an overall Power-to-X process. Using digital modeling in both the design and the engineering phase (known as the digital twin) allows (for example an optimal sizing of the assets) an optimization in the digital world before installing anything on site.

5. The power of now: The hydrogen economy starts today

Worldwide decarbonization of the overall energy systems is urgently needed to mitigate global warming. Power from renewables will become the backbone of a green energy supply through sector coupling. The different pathways of Power-to-X will enable this development which can start immediately since the infrastructure for transport, distribution and final use of e-Fuels already exists in principle.

The outlook is even brighter. Thanks to Power-to-X, largely carbon-neutral or even carbon-free mobility based on e-Fuels and/or green hydrogen will be the norm, not the exception.

Obligations to increasingly apply e-Fuels in the mobility sector like those already implemented for biomass-based fuels, together with other measures like increasing penalties for CO_2 emissions, would promote the introduction of Power-to-X. And compared to other sustainable energy carriers, mostly biomass-based fuels, e-Fuels are already competitive.

Siemens Energy pushes Power-to-X with its different variants. For Power-to-Heat, a high-temperature heat pump has been developed. Siemens Energy is deeply engaged in promoting and developing projects and technologies for the production of green hydrogen and subsequent products. With its Silyzer portfolio, Siemens Energy is leading PEM-based water electrolysis, which allows for a highly flexible load operation and is, thus, predestined for combination with volatile renewable energy sources. Wind generators, compressor solutions, gas turbines and combined cycle power plants for reelectrifcation of green hydrogen are all part of the portfolio, as well as the overall business solutions to realize small to large-scale Power-to-X plants.

Hand in hand with our clients and partners, Siemens Energy is ready to go!

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Siemens Energy is one of the world's leading energy technology companies. The company works with its customers and partners on energy systems for the future, thus supporting the transition to a more sustainable world. With its portfolio of products, solutions and services, Siemens Energy covers almost the entire energy value chain – from power generation and transmission to storage. The portfolio includes conventional and renewable energy technology, such as gas and steam turbines, hybrid power plants operated with hydrogen, and power generators and transformers. More than 50 percent of the portfolio has already been decarbonized. A majority stake in the listed company Siemens Gamesa Renewable Energy (SGRE) makes Siemens Energy a global market leader for renewable energies. An estimated one-sixth of the electricity generated worldwide is based on technologies from Siemens Energy. Siemens Energy employs more than 90,000 people worldwide in more than 90 countries and generated revenue of around €27.5 billion in fiscal year 2020. www.siemens-energy.com

